

# PUZZLING AFTERGLOW's OSCILLATIONS IN GRBs AND SGRs: TAILS OF PRECESSING JETS

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## Abstract

Damped oscillating afterglows in GRB 030329 and in SGR 1900+14 find a natural explanation in precessing  $\gamma$  Jet model for both GRBs and SGRs. The very thin Jet cone  $\frac{\Delta\Omega}{\Omega} \leq 10^{-8}$  combines at once the Supernova power and the apparent huge GRBs output:  $\dot{E}_{GRBs} \simeq \dot{E}_{SN} \frac{\Omega}{\Delta\Omega}$  leading to a better understanding of their remarkable GRB-Super Nova connection shown in early GRB980425/SN1998bw event and in most recent GRB030329/SN2003dh one. The same thin beaming offer a understanding of the apparent SGR-Pulsar power connection:  $\dot{E}_{SGRs} \simeq \dot{E}_{Xpuls} \frac{\Omega}{\Delta\Omega}$ . The precessing Jet model for both GRBs and SGRs, at their different luminosity, explains the existence of a few identical energy spectra and time evolution of these two sources leading to their unified understanding. The spinning-precessing Jet explains the rare mysterious X-Ray precursors in GRBs and SGRs. The Multi-precessing Jet at peak activity in all band may explain the puzzling X or optical re-brightening bumps found in last GRB030329 and earliest SGR 1900 + 14 on 27 August 1998 and on 18 April 2001, as well as the multi-bump radio light-curve observed in GRB980425 and GRB030329. Rarest micro-quasars in our galaxy as SS433, and Herbig Haro objects describe these thin precessing Jet imprint in their 3D relic nebulae shapes.

# 1 INTRODUCTION

The very clear imprint of gamma polarization in the  $\gamma$  signals from GRB021206 [1] probes to the eyes of most skeptical Fireball theorist the very presence of a thin collimated jet (opening angle  $\Delta\theta \leq 0.6^\circ$ ;  $\frac{\Delta\Omega}{\Omega} \leq 2.5 \cdot 10^{-5}$ ) in Gamma Ray Burst, GRBs. The very last and well proved GRB030329/SN2003dh time and space coincidence confirms definitively the earliest GRB980425/SN1998bw connection among GRB and Supernova. Therefore the apparent extreme GRBs luminosity is just the extreme beamed blazing gamma Jet observed in axis during a Supernova event. Indeed (or moreover) the maximal isotropic SN power,  $\dot{E}_{SN} \simeq 10^{45} \text{ erg s}^{-1}$ , because of very probable energy equi-partition, should be collimated even into a more thinner jet  $\frac{\Delta\Omega}{\Omega} \leq 10^{-8}$ , in order to explain at once the apparent observed maximal GRBs output,  $\dot{E}_{GRB} \simeq 10^{53} \text{ erg s}^{-1}$ . Consequently one-shoot thin Jet GRBs needs many more  $\dot{N}_{GRBs} \simeq \frac{\Omega}{\Delta\Omega} \geq 10^8$  events than any spread isotropic Fireballs. Such a rate exceed even the known Supernova one. To overcome the puzzle a persistent precessing decaying jet (life-time  $\tau_{Jet} \geq 10^3 \tau_{GRB}$ ) is compelling. Relic GRBs sources may be found in compact SNRs core, as NS or BH jets; at later epoch, their lower power  $\gamma$  jets may be within detectability only from nearby galactic distances, as Soft Gamma Repeaters (SGRs) or anomalous X-ray Pulsars, AXPs. This common Jet nature explain some connection between GRBs and SGRs. Indeed rare spectra of SGRs behaved as GRBs. Also X-Ray precursors in GRBs as well as in SGRs suggest the needed for a precessing Jet model. A surprising multi re-brightening afterglows observed in early and late GRB 030329 optical transient, like in the 27 August 1998 and 18 April 2001 SGR 1900 + 14 events, might be the damped oscillatory imprint left by such a multi-precessing  $\gamma$ -X-Optical and Radio Jet.

## 1.1 The different GRBs puzzles

Gamma Ray Burst mystery lays in its huge energy fluence, sharp variability, extreme cosmic distances and very different morphology. A huge isotropic explosion (the so called Fireball) was the ruling wisdom all along last decade. However shortest millisecond time scales called for small compact objects, so contained and confined to became opaque, because abundant pair production, to their own explosive luminosity (over Eddington luminosity) and so small in size and in masses (few solar masses) to be unable to supply themselves the needed larger and larger isotropic energies. The spectra, in a Fireball, had to be nearly thermal, contrary to data. Fireball be-

came shell by shell an hybrid complex model, where power law after power law, it tried to fit each complex GRBs spectra and time evolution. The huge GRBs powers as GRB990123 made the final collapse of the Fireball model. New families of Fire-Ball Jet (and their label names like Hyper-Nova, Supra-Nova, Collapsar ) models alleviated, by a Jet beaming, the explosive energy budget request. However in this compromise attitude the puzzle of the GRB980425/SN1998bw (which require a very thin Jet observed off-axis [19],[12]) has been cured by most skeptical authors by a tenacious cover-up (neglecting or refuting The GRB-SN existence) or claiming the co-existence of an new zoo of GRBs [3],[17]. These new compromised fountain-like Fireball model has been collimated in a Jet within a  $10^\circ$  angle beam, as a soft link between past Fireball and emerging Jet. However the apparent required GRB power output is still huge ( $10^{50} \text{ erg s}^{-1}$ ), nearly  $10^5$  more intense than other known maximal explosion power (the Super-Nova one). More and more evidences in last years and more recently have shown that Super-Nova might harbor a collimated Jet Gamma Ray Burst (GRB980425/SN1998bw ,GRB030329/SN2003dh). To combine the Super-Nova Luminosity and the apparent huge GRBs power one need a very much thinner beam jet, as small as a solid angle  $\Delta\Omega/\Omega \simeq 10^{-7}$  or  $10^{-8}$  respect to  $\Omega \simeq 4\pi$ , (corresponding to a Jet angle  $0.065^\circ - 0.02^\circ$  ). There is a statistical need [12] to increase the GRB rate inversely to the beam Jet solid angle. The needed SN rate (to explain GRBs) may even exceed the observed one (at least SN type Ib and Ic) event in our observable Universe ( $N_{NS} \leq 30s^{-1}$ ). Indeed assuming that only a fraction of the SN (with optimistic attitude 0.1 of all known SN) experience an asymmetric Jet-SN explosion, than the corresponding observed rate  $N_{GRBs} \simeq 10^{-5}s^{-1}$  and  $N_{SN} \simeq 3s^{-1}$  imply  $\frac{N_{GRBs}}{\frac{\Delta\Omega}{\Omega}} \simeq 10^2s^{-1} \longleftrightarrow 10^3s^{-1}$  a result nearly 2 – 3 order of magnitude larger than the observed SN rate. In this frame one must assume a GRB Jet with a continuous active, decaying life-time much larger than GRBs duration itself at least by a corresponding scale  $\tau_{Jet} \simeq 10^3\tau_{GRBs}$ . Indeed we considered GRBs (as well as Soft Gamma Repeaters SGR) as very thin blazing ( $\leq 0.1^\circ$ ) precessing Gamma Jets spinning and precessing [4],[8],[5],[7],[12],[13]; in this scenario GRBs are born within a Super-Nova power collimated inside a very thin beam able to blaze us by an apparent GRB intensities. The inner angle geometrical dynamics while spinning and precessing induce the wide  $\gamma$  burst variability able to fit the very different observed GRBs ones.

The averaged  $\gamma$  jet deflection from the axis of sight defines a main early power law decay; an inner damped oscillatory substructure may be observed, as the amazing damping oscillatory afterglows in GRB030329. The very thin

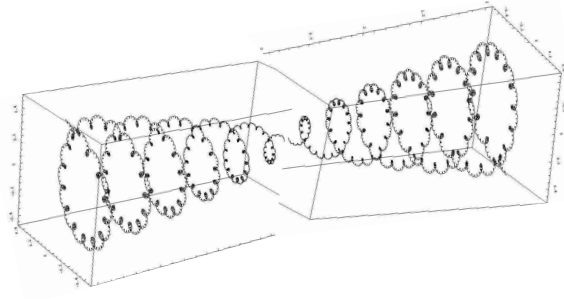


Figure 1: A possible inner structure 3D of a multi precessing Jet; its cone structures and its stability at late stage it maybe reflected in the quasi-periodic repetitions of the Soft Gamma Repeaters while beaming to us along the cone edges toward the observer. Its early blast at maximal SN out-put may simulate a brief blazing GRBs event, while a fast decay (hours scale) may hide its detectability below the threshold, avoiding in general any common GRB repeater.

and collimated and long life decaying jet (opening angle  $\theta \leq 0.05^\circ$ , whose decay power law life-time of a few hours occurs with an exponent  $\alpha \simeq -1$ ), while spinning and precessing at different scale times, it may trace and may better explain the wobbling of the  $\gamma$  GRBs and the long train of damped oscillations of the X tail afterglows within hours, the optical transient during days and weeks later. The GRBs re-brightening are no longer a mystery as in a one-shoot model. These wobbling signatures may be also be found in rarest and most powerful and studied SGRs events. The spread and wide conical shape of these precessing twin jets may be recognized in a few relic SNRs as in the twin SN 1987A wide external rings, the Vela arcs and the spectacular Egg Nebula dynamical shape.

## 1.2 The geometrical multi-precessing Gamma Jet in GRB

We imagine the GRB and SGR nature as the early and the late stages of jets fueled first by SN event and later by an asymmetric accretion disk or a companion (WD, NS) star.

Their binary angular velocity  $\omega_b$  reflects the beam evolution  $\theta_1(t) = \sqrt{\theta_{1m}^2 + (\omega_b t)^2}$  or more generally a multi-precessing angle  $\theta_1(t)$  [8],[9]:

$$\theta_1(t) = \sqrt{\theta_x^2 + \theta_y^2}$$

$$\theta_x(t) = \theta_b \sin(\omega_b t + \varphi_b) + \theta_{psr} \sin(\omega_{psr} t + \varphi_{psr}) + \theta_N \sin(\omega_N t + \varphi_N)$$

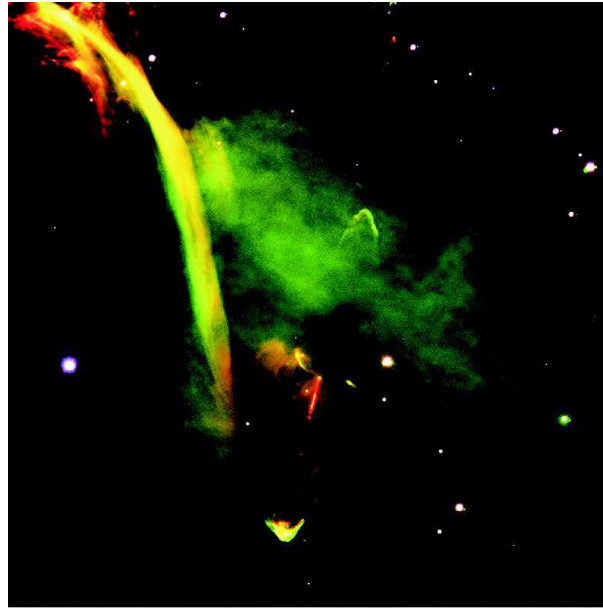


Figure 2: Egg Nebula Twin Conical Shape. Such a mysterious twin cone picture maybe easily understood within a precessing Jet source well hidden in the center of the nebula whose presence is made evident by the help of a diffused nearby cloud target

$$\theta_y(t) = \theta_{1m} + \theta_b \cos(\omega_b t + \varphi_b) + \theta_{psr} \cos(\omega_{psr} t + \varphi_{psr}) + \theta_N \cos(\omega_N t + \varphi_N) \quad (1)$$

where  $\theta_{1m}$  is the minimal impact angle parameter of the jet toward the observer,  $\theta_b$ ,  $\theta_{psr}$ ,  $\theta_N$  are, in the order, the maximal opening precessing angles due to the binary, spinning pulsar, nutation mode of the multi-precessing jet axis. The arbitrary phase  $\varphi_b$ ,  $\varphi_{psr}$ ,  $\varphi_N$ , for the binary, spinning pulsar and nutation, are able to fit the complicated GRBs flux evolution in most GRB event scenario. Naturally it is very possible to enlarge the parameter to a fourth precession angular component whose presence may better fit the wide spread of scale variability; here we shall constrain to a three parameter precession beam.

For a 3D pattern and its projection along the vertical axis in an orthogonal 2D plane see following descriptive pictures. The different angular velocities are combined in the multi-precession wobbling. Each bending component is keeping memory either of the pulsar jet spin angular velocity ( $\omega_{psr}$ ) and its opening angle  $\theta_{psr}$ , its nutation speed ( $\omega_N$ ) and nutation angle  $\theta_N$  (due to possible inertial momentum anisotropies or beam-accretion disk torques); a slower precession by the binary  $\omega_b$  companion (and its corresponding open angle  $\theta_b$ ) will modulate the overall jet precession. On average, from eq.(3) the  $\gamma$  flux and the  $X$ , optical afterglow are decaying on time as



Protostar HH-34 in Orion (VLT KUEYEN + FORS2)

ESO PR Photo 40ly99 (17 November 1999)

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Figure 3: A whip behaviour of HH34 micro-quasar narrow Jet. The long tail of the jet in both near by and far side describes a thin moving jet; an internal spinning sub-structure may be hidden inside the strip jet width.

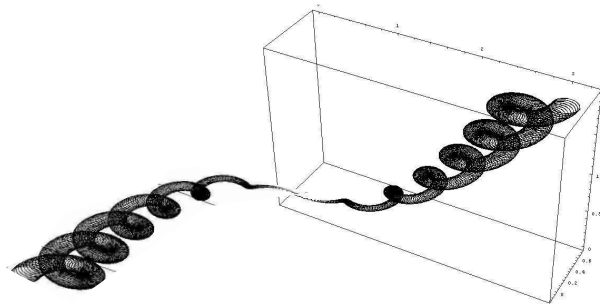


Figure 4: A twin spinning and precessing jet configuration whose appearance on line of sight, when at maximal supernova output, may blaze as the sudden GRBs; at much later and less powerful stages, while behaving as an X-Ray pulsar, it may rarely blaze as a SGRs from nearby, galactic like distances.

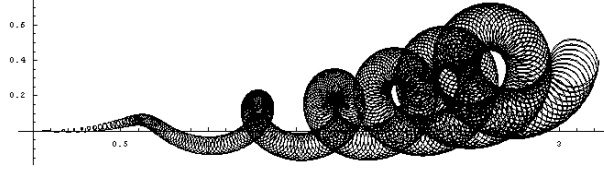


Figure 5: The consequent twin spinning and precessing jet configuration projected onto a 2dimensional screen whose blazing appearance on line of sight, at SN may appear as the sudden GRBs or later at less powerful stages as a SGRs from nearby distances.

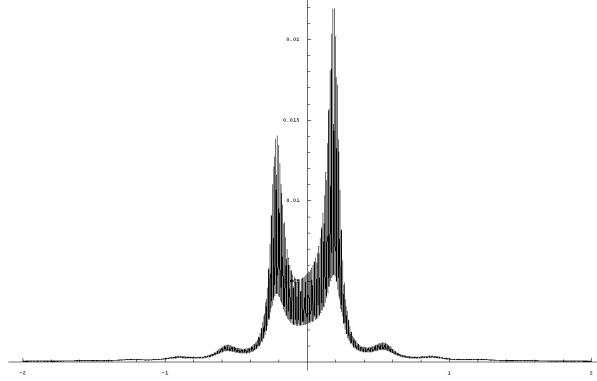


Figure 6: Multi bump afterglow behaviour of the intense precessing Jet above whose blazing shows the characteristic oscillatory damped decay as the recent GRB 030329 and the intense SGR on 27 August 1998. The luminosity starting time is assumed near zero ( at SN birth time). In present simulation the assumed Lorents factor is  $\gamma_e = 2 \cdot 10^3$

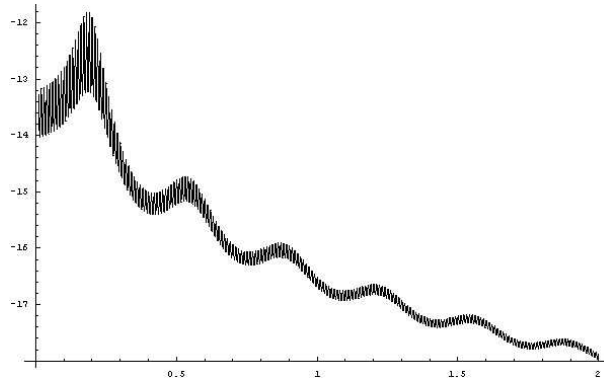


Figure 7: Multi bump Flux Intensity behaviour in linear scales, normalized to visual magnitude for a previous precessing Jet simulating the characteristic oscillatory damped decay as the recent GRB 030329 and the intense SGR on 27 August 1998; time scale are arbitrary; in the GRB 030329 the unity corresponds to nearly day scale while in SGR event the unity in much smaller minute scale

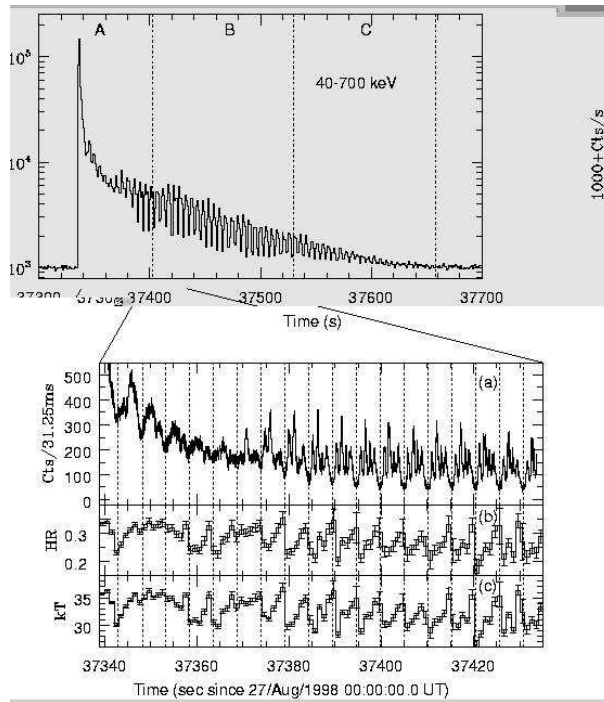


Figure 8: Multi bump behaviour of the intense SGR on 27 August 1998, showing the characteristic oscillatory damped decay as GRB 030329 described above



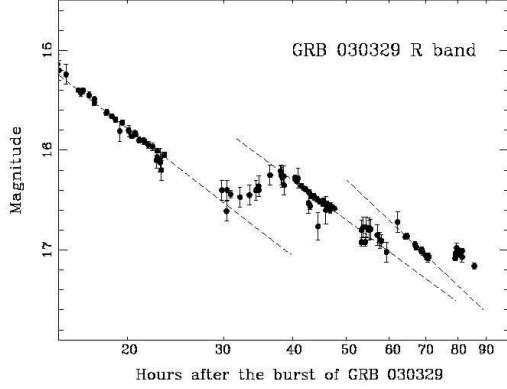


Figure 9: The multi bump behaviour or re-brightening of the oscillatory damped decay observed in GRB 030329; its puzzling imprint maybe described by a precessing  $\gamma$ , X and optical jet

$t^{-\alpha}$ , where  $\alpha \simeq 1 - 2$ ; however the more complicated spinning and precessing jet blazing is responsible for inner small scales wide morphology of GRBs and SGRs as well as their partial internal periodicity. The consequent  $\gamma$  time evolution and spectra derived in this ideal models may be compared successfully with observed GRB data evolution.

## 2 Hard $\gamma$ -X Jet by Inverse Compton Scattering

The  $\gamma$  Jet is born mainly by Inverse Compton Scattering by GeVs electron pairs onto thermal photons [4] [5], [6],[10], [12] in nearly vacuum space. Therefore these electron pairs are boosted in the Jet at Lorentz factor  $\gamma_e \geq 2 \cdot 10^3$ . Their consequent Inverse Compton Scattering will induce a parallel  $\gamma$  Jet whose beam angle is  $\Delta\theta \leq \frac{1}{\gamma} \simeq 5 \cdot 10^{-4} rad \simeq 0.0285^\circ$  and a wider, less collimated X, Optical cone. These beaming angles agree with the one assumed to explain the required beamed GRBs-SN powers. Indeed the electron pair Jet may generate a secondary beamed synchrotron radiation component at radio energies, in analogy to the behaviour of BL Lac blazars whose hardest TeV  $\gamma$  component is made by Inverse Compton Scattering while its correlated X band emission is due to the synchrotron component. Anyway the inner jet is dominated by harder photons while the external cone contains softer X, optical and radio waves. A jet angle related by a relativistic kinematics would imply  $\theta \sim \frac{1}{\gamma_e}$ , where  $\gamma_e$  is found to reach

$\gamma_e \simeq 10^3 \div 10^4$  [12],[9]. At first approximation the gamma constrains is given by Inverse Compton relation:  $< \epsilon_\gamma > \simeq \gamma_e^2 kT$  for  $kT \simeq 10^{-3} - 10^{-1} \text{ eV}$  and  $E_e \sim \text{GeV}$ s leading to characteristic X- $\gamma$  GRB spectra. The origin of  $\text{GeV}$ s electron pairs are very probably decayed secondary related to primary inner muon pairs jets, able to cross dense stellar target [10] . The consequent adimensional photon number rate as a function of the observational angle  $\theta_1$  responsible for peak luminosity becomes [12]

$$\frac{\left(\frac{dN_1}{dt_1 d\theta_1}\right)_{\theta_1(t)}}{\left(\frac{dN_1}{dt_1 d\theta_1}\right)_{\theta_1=0}} \simeq \frac{1 + \gamma^4 \theta_1^4(t)}{[1 + \gamma^2 \theta_1^2(t)]^4} \theta_1 \approx \frac{1}{(\theta_1)^3} . \quad (2)$$

The total fluence at minimal impact angle  $\theta_{1m}$  responsible for the average luminosity is

$$\frac{dN_1}{dt_1}(\theta_{1m}) \simeq \int_{\theta_{1m}}^{\infty} \frac{1 + \gamma^4 \theta_1^4}{[1 + \gamma^2 \theta_1^2]^4} \theta_1 d\theta_1 \simeq \frac{1}{(\theta_{1m})^2} .$$

These spectra fit GRBs observed ones [9],[5],[6], [12]. Assuming a beam jet intensity  $I_1$  comparable with maximal SN luminosity,  $I_1 \simeq 10^{45} \text{ erg s}^{-1}$ , and replacing this value in the above a-dimensional equation we find a maximal apparent GRB power for beaming angles  $10^{-3} \div 3 \times 10^{-5}$ ,  $P \simeq 4\pi I_1 \theta^{-2} \simeq 10^{52} \div 10^{55} \text{ erg s}^{-1}$ , just within observed ones. We also assumed a power law jet time decay as follows

$$I_{jet} = I_1 \left(\frac{t}{t_0}\right)^{-\alpha} \simeq 10^{45} \left(\frac{t}{3 \cdot 10^4 \text{ s}}\right)^{-1} \text{ erg s}^{-1}$$

where ( $\alpha \simeq 1$ ) is a value able to reach, at 1000 years time scales, the present known galactic micro-jet (as SS433) intensities powers:  $I_{jet} \simeq 10^{39} \text{ erg s}^{-1}$ . This offer a natural link between the GRB and the SGR out-put powers. We used the model to evaluate if April precessing jet might hit us once again. It should be noted that a steady angular velocity would imply an intensity variability ( $I \sim \theta^{-2} \sim t^{-2}$ ) corresponding to some of the earliest afterglow decay law. These predictions have been proposed since a long time, [12]. Similar descriptions with more parameters and within a sharp time evolution of the jet has been also proposed by other authors [2],[18].

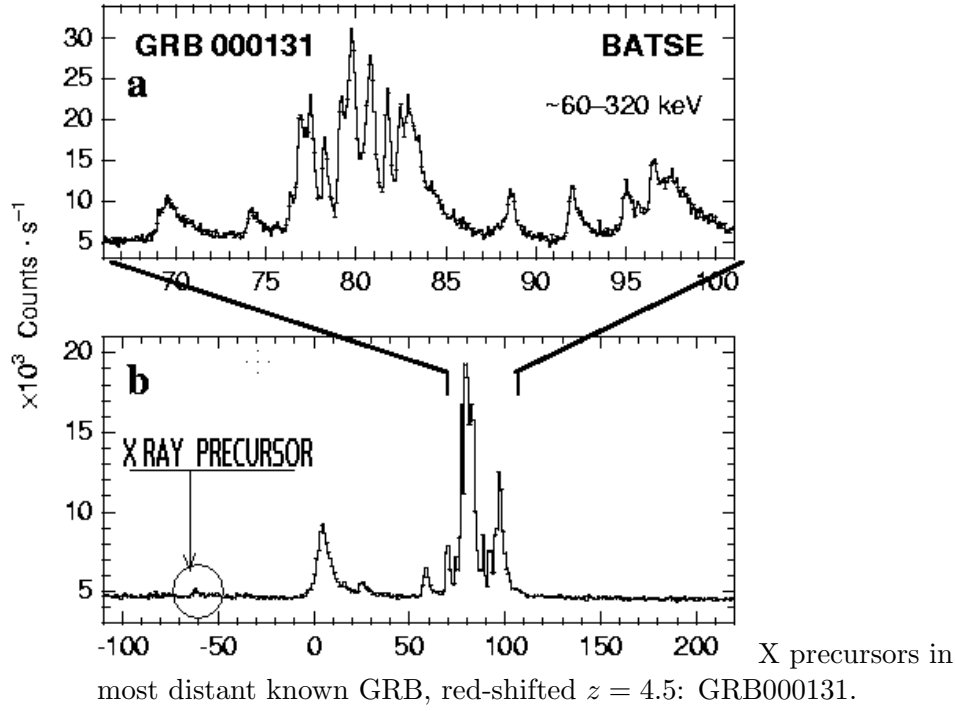
## 2.1 Precessing Radio Jet by Synchrotron Radiation

The same GeVs electron pair Jet may generate a secondary beamed synchrotron radiation component at radio energies, in analogy to the behaviour

of BL Lac blazars whose hardest TeV  $\gamma$  component is made by Inverse Compton Scattering while its correlated X band emission is due to the synchrotron component. Anyway the inner jet is dominated by harder photons while the external cone contains softer X, optical and radio waves. Their precessing in wide angle is the source of the radio bumps at days scale times clearly observed recently in GRB980425, GRB030329 light curves. The very peculiar oscillating GRB970508 optical variability did show a re-brightening nearly two months later, did also show a remarkable multi-bump variability in radio wave-length. For this reason and we are more inclined to believe that this fluctuations were indeed to be related to the Jet precession and not to any interstellar scintillation. There is not any direct correlation between the  $\gamma$  Jet made up by I.C. scattering and the Radio Jet because the latter is dominated by the external magnetic field energy density: there maybe a different beaming opening and a consequent different time modulation respect to the inner  $\gamma$  Jet. However the present wide energy power emission between SN2002ap and GRB030329 radio light curves makes probable a beaming angle comparable:  $\leq 10^{-3} - 10^{-4}$  radiant.

### 3 X Ray precursor by Precessing Jet

The thinner the jet, the wider the sample and the source volume (largest redshift) and the harder is the  $\gamma$  Jet observed. This explain why, in opposite behaviour respect to the Hubble cosmic expansion and to the time dilution, the observed hardest GRBs spectra and the most variable and the most power-full ones are not the nearest but the most distant ones. Isotropic explosions are out of this frame. Indeed the extreme  $\gamma$  energy budget, calling for a comparable  $\nu$  one, exceeds few or many solar masses in isotropic models emission even for ideal full mass-energy conversion. To judge the fitting of the Jet model let us consider the most distant  $z = 4.5$  known GRB event: GRB000131 and its X ray precursor. This event while being red-shifted and slowed down by a factor 5.5 exhibited on the contrary shows a short scale time and a very fine structure in disagreement with any fire-ball model, but well compatible with a thin, fast spinning precessing  $\gamma$  jet. Indeed let us notice the presence of a weak X-ray precursor pulse lasting 7 sec, 62 sec before the huge main structured  $\gamma$  burst trigger GRB000131 [13]. Its arrival direction (within 12 degree error) with main GRB is consistent only with the main pulse (a probability to occur by chance below  $3.6 \cdot 10^{-3}$ ). The time clustering proximity (one minute over a day GRB rate average) has the probability to occur by chance below once over a thousand.



The over all probability to observe this precursor by chance is below 3.4 over a million making inseparable its association with the main GRB000131 event. This weak burst signal correspond to a power above a million Supernova and have left no trace or Optical/X transient just a minute before the real (peak power > *billion* Supernova) energetic event. No isotropic GRB explosive progenitor could survive such a disruptive isotropic (million supernova output) precursor trigger nor any multi-exploding jet. Only a persistent, pre-existing precessing Gamma Jet crossing twice nearby the observer direction could naturally explain this luminosity evolution. These X-ray precursor are not unique but are found in 3–6% of all GRBs. Similar X precursors occurred in SGRs event as the  $1900 \pm 14$  on 29 August 1998.

#### 4 Conclusions: Neutrino-Muon Jets Progenitors

We believe that GRBs and SGRs are persistent blazing flashes from lighthouse thin  $\gamma$  Jet spinning in multi-precessing (binary, precession, nutation) mode. These GRBs Jets are originated by NSs or BH in binary system or disk powered by infall matter; their relics (or they progenitors) are nearly

steady X-ray Pulsars whose fast blazing is source of SGRs. The Jet is not a single explosive event even in GRB, but they are powered at maximal output during a long period of SN event. The beamed Jet power is comparable to SN ones at its peak luminosity; this external  $\gamma$  Jet has a chain of progenitor identities: it is born in most SN and or BH birth and it is very probably originated by a very collimated inner primary muon Jet pairs at TeVs-PeVs energies. These muons could cross with negligible absorption the dense target lights along the SN explosions, nearly transparent to photon-photon opacities. We speculate that these muon pair progenitors might be themselves secondary relics beamed by ultra-high energy neutrino Jet originated in the very interior of the new born NS or BH, neutrino able to escape quite dense matter envelopes obscuring the Super-Nova volume [14],[15]. The high energy relativistic muons (tens TeVs-PeVs energies) decay in flight in electron pairs where the baryon density is still negligible; these muons are source, by decay in flight to TeVs-GeV electron pair showering whose final Inverse Compton Scattering with nearby thermal photon is the final primary of the observed hard  $X - \gamma$  Jet. The cost of this long chain of reactions is a poor energy conversion, but the benefit is the possibility to explain the  $\gamma$  escape from a very dense explosive and polluted (by matter and radiation) narrow volume. The relativistic morphology of the Jet and its multi-precession geometry is the source of the complex  $X - \gamma$  spectra signature of GRBs and SGRs. Its inner Jet ruled by relativistic Inverse Compton Scattering, has the hardest and rarest beamed GeVs-MeVs photons (as the rare and long 5000 s life EGRET GRB940217 one) but its external Jet cones are dressed by softer and softer photons. This onion like multi Jets is not totally axis symmetric: it may show itself while spinning and turning and spraying around in a deformed (often and in particular in fast GRBs) elliptical onion off-axis rings, out-of-center; therefore ones their internal harder core at the extreme edges are leading to a most common hard to soft GRBs  $\gamma - X$  train signal. Nevertheless this is not the rule. In our present model and simulation this internal effect has been neglected without any major consequence. The complex variability of GRBs and SGRs are simulated successfully by the equations above [5],[7],[12]; the consequent geometrical beamed Jet blazing may lead also to the observed widest morphology  $X - \gamma$  signatures. The mystery therefore is not longer in an apparent huge GRB luminosity, but in an extreme beam jet collimation and precession.

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